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1. Introduction

The welding of aluminum and its alloys has always represented a great challenge for designers and technologists. Aluminum alloys, especially heat-treatable aluminum alloys, are difficult to join by fusion welding techniques. Friction stir welding (FSW) a solid-state joining process developed and patented by the The Welding Institute (TWI) [1], emerged as a welding technique to be used in high strength alloys (2xxx, 6xxx, 7xxx and 8xxx series) for aerospace, automotive and marine applications that were difficult to join with conventional techniques. The process was developed initially for aluminium alloys, but since then FSW was found suitable for joining a large number of materials. Conventional fusion welding of aluminium alloys often produces a weld which suffers from defects, such as porosity developed as a consequence of entrapped gas not being able to escape from the weld pool during solidification [2]. In FSW a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. The tool serves two primary functions: (a) heating of work piece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in 'solid state'. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains. The fine microstructure in friction stir welds produces good mechanical properties.

1.1 Objectives of the Present Research Work

Over the past two decades numerous research studies have been undertaken in order to characterize the process in terms of mechanical & metallurgical characterization and its effect on mechanical properties such as yield strength, tensile strength and percentage of elongation and fatigue properties, material flow, mechanical response by numerical simulation, thermo-mechanical model, tool process parameters & the corrosion behaviour of a FSW joints. This is all discrete work & it is observed that there is no evidence of systematic work that leads to development of quality joint for similar as well as dissimilar metal welds based on systematic variation of tool geometry & measure process parameters. The objective of present research work aims to acquire the fundamental knowledge of the FSW process and to investigate the feasibility of incorporating this technology with existing resources to weld aluminium alloys in the abutting configuration and characterize the optimum operating parameters while establishing sound mechanical integrity of the friction stir welded joint.

In aerospace industry the basic aluminium alloys are 2xxx and 7xxx but, presently, the 6xxx aluminium alloys creates a particular interest not only for researchers but also for the experts of the industries. This 6xxx aluminium alloys have many advantages such as medium resistance, plasticity, good welding characteristics, corrosion resistance and a low cost. Besides, applying thermal treatments, the 6xxx aluminium alloys are used in many applications (the exterior of the planes fuselages, panels and even in automotive shock absorbers), in the detriment of the 2xxx and 7xxx alloys. In present research work an attempt is made to investigate the effect of weld process parameters on the quality of the FSW joint of aluminium alloys AA6082 & AA6061 having plate thickness of 5mm.

2. History and Invention of Friction Stir Welding

Developed by The Welding Institute (TWI) [1] the Friction Stir Welding (FSW) process was invented and patented in 1991 meaning that in terms of a manufacturing process it is a relatively new one. FSW is a modification on an already known method of joining metal via frictional heating known simply as Friction welding. Friction welding is a joining process which has been in development for more than 100 years. This form of joining is most suited to material which is in rod or pipe form. It involves rotating or oscillating one rod whilst keeping the other stationary. The two are brought together and friction results. This in turn causes heat. Once sufficient heat has been generated the two rods are pushed together with a force which forges the two rod sections together. The excess extruded material from the circumference of the join can then be removed leaving a welded section.

In FSW the heat is generated by a non-consumable tool which is rotated at high speed, plunged into and traversed through the material creating a join at the rear of the tool. The forging force in this case is the downwards force exerted by the spindle. The friction stir welding process is a simple one by its nature. It uses simple technology to produce state-of-the-art joins in previously difficult to weld or un-weldable materials. The processing steps of FSW result in material positioning, tool plunge, tooling traverse and pull out/run off.

3. Literature Review

Friction-stir welding (FSW) is a solid-state joining process for metallic and a few polymeric materials which is generally employed in applications in which the original material microstructure & properties must remain unchanged as much as possible after joining [1–3]. FSW is produced by rotating and plunging a specially-designed cylindrical, shouldered tool with a small diameter pin into the joint line between two butted plates. Frictional heat causes the metal to soften and allows the tool to traverse along the joint line. The two plates are clamped on a rigid backing support. The fixturing prevents the

plates from spreading apart or lifting during welding. The welding tool, consisting of a shank, shoulder and pin, is then rotated to a prescribed speed. The tool is slowly plunged into the workpiece material at the butt line, until the shoulder of the tool forcibly contacts the upper surface of the material and the pin is a short distance from the back plate. A downward force is applied to maintain the contact and a short dwell time is observed to allow for the development of the thermal fields for preheating and softening the material along the joint line. At this point, a lateral force is applied in the direction of welding (travel direction) and the tool is forcibly traversed along the butt line until it reaches the end of the weld. Alternately, the plates could be moved while the rotating tool remains stationary. Upon reaching the end of the weld, the tool is withdrawn while it is still being rotated. As the pin is withdrawn, it leaves a keyhole at the end of the weld. It should be recognized that FSW can be used not only for butt joining but also for lap as well as T joints. The FSW process of butt joints is shown in fig. 1

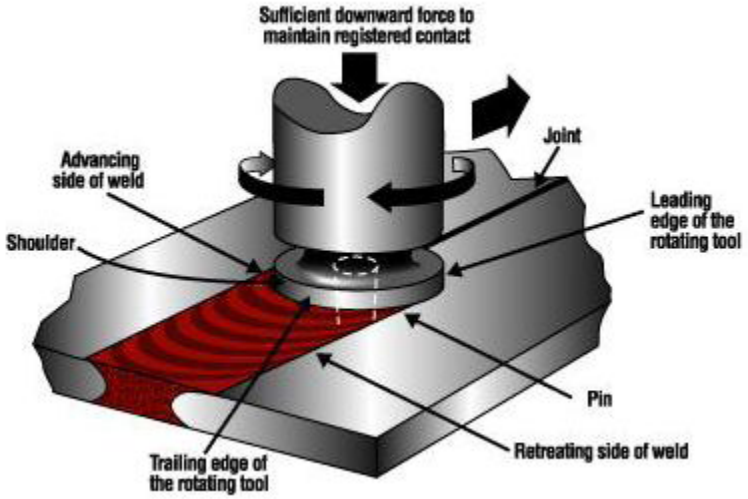

Figure-1 Principle of the FSW process for butt joints.

The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side.

Since its discovery in 1991 [1], FSW has established itself as a preferred joining technique for aluminum components and its applications for joining other difficult-to-weld metals is gradually expanding. Currently, this joining process is being widely used in many industrial sectors such as shipbuilding and marine, aerospace, railway, land transportation, etc. [4]

FSW involves complex interactions between varieties of simultaneous thermo-mechanical processes. During FSW, the tool moves along the weld joint at a constant speed, as it rotates about its axis heat is generated by friction between the tool and the work piece and resulting plastic deformation. A typical cross-section of the FSW joint consists of four distinct numbers of zones: (A) base metal, (B) heat–affected, (C) thermo-mechanically affected and (D) stirred (nugget) zone (Fig. 2) [5, 6]. The Heat–Affected Zone (HAZ) is similar to that in conventional welds although the maximum peak temperature is significantly less than the solidus temperature, and the heat– source is rather diffuse. The central nugget region is the one which experiences the most severe deformation, and is a consequence of the way in which a tool deposits material from the front to the back of the weld. The Thermo Mechanically Affected Zone (TMAZ) lies between the HAZ and nugget; the grains of the original microstructure are retained in this region, but often in a deformed state. A unique feature of the friction stir welding process is that the transport of heat is aided by the plastic flow of the substrate close to the rotating tool. The heat and mass transfer depend on material properties as well as welding variables including the rotational and welding speeds of the tool and its geometry. In FSW, the joining takes place by extrusion and forging of the metal at high strain rates. Jata et.al estimated a typical deformation strain rate of 10 s^{-1} by measuring grain-size and using a correlation between grain-size and Zener-Holloman parameter which is temperature compensated strain-rate [7]. Kokawa et al. estimated an effective strain rates in the range 2–3 s^{-1} [8].

Although currently FSW can be used to join several materials such as magnesium [9-10], copper [11–13], steel [14–17], titanium [18,19] and MMCs [20,21], the primary research and industrial interest for this process was for butt and lap joining of aluminium alloys, especially the 2XXX, 6XXX and 7XXX series of heat treatable aluminium alloys, usually considered to be ‘‘unweldable”. Concerning the FSW of the 6XXX series of aluminium alloys, the 6061 series was studied, either in similar [22-32] and dissimilar [33-43] welding combinations. Also the effort was spent in studding the FSW of the 6082 [44-54], 6063 [55-60], 6056 [61-63], 6022 [64-65], 6005 [66-67], 6013 [68] and 6016 [69] series of alloys. In most of these studies the thicknesses of the plates joined ranged from 3 to 6 mm. FSW results in generation of various microstructural zones- the nugget zone, the TMAZ, and the HAZ. These zones exhibit different microstructural characteristics such as grain size and dislocation density, residual stress and texture, and precipitate size and distribution. Therefore, it is expected that the various microstructural zones will exhibit different corrosion behaviour. For practical applications, it is very important to understand corrosion behaviour of the FSW welds and elucidate the prevailing mechanisms for corrosion in various FSW alloys and various microstructural zones. In the

past few years several studies were conducted with the aim to understand the effect of FSW on the corrosion and stress corrosion cracking [70-74].

Despite the large amount of published literature about the FSW process, systematic information does not exist on the influence of the tool geometry and the process parameters on the weld quality for a large range of materials, thicknesses and joint configurations. The objective of present research work aims to acquire the fundamental knowledge of the FSW process and to investigate the feasibility of incorporating this technology with existing resources to weld aluminium alloys 6xxx in the abutting configuration and characterize the optimum operating parameters while establishing sound mechanical integrity of the friction stir welded joint.

4. The Research Methodology

4.1 Material and Welding Conditions: The crucial part in this research work was to develope an experimental setup (Fig-2) which would fit in the available machine tool The friction stir welds have been carried out by using a properly designed clamping fixture that allows the user to fix the two sheets of required dimension with plate thickness of 5mm to be but welded on manual vertical milling machines & MORI SEIKI SV-50 vertical machining centre (VMC). The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was used to fabricate the butt joints. Non-consumable tool made of Cold Work Die Steel (WPS) have been used to fabricate the joints which is oil quenched at hardening temperature of 920-980^{0}C, & tempering temperature of 100-350^{0}c and characterized by 58 to 65 HRC hardness. The dimension of tool was, tool shoulder diameter =18 mm & tool pin length =4.7 mm.

Figure-2 Experimental Setup describing clamping and welding of FSW plates.

For the present investigation, aluminum alloys AA6082-O/T_6 and AA6061-T_6 were chosen for the fabrication of similar FSW joints. These alloys are widely used in aerospace applications because of good formability, weldability, machinabilty, corrosion resistance and high strength compared to other aluminum alloys.

Further to FSW joints of similar alloys, FSW is being studied for welding dissimilar alloys which can be of particular interest in some industrial applications. Some works can be found in the literature, but data is still scarce on the characterisation of this joint type. In this work the ability to join dissimilar alloys by FSW was studied using butt welded plates. The mechanical & metallurgical characterization of friction stir welds of aluminium alloy 6082-T6 with 6061-T6 was carried out. The present research work investigates the results of an experimental setup in which the aluminium alloy AA6082-T6 & AA6061-T6 was FS Welded, using various combinations of process parameters i.e. rotational, travel speed and axial force and different tool pin profiles like cylindrical tri flute, cylindrical taper screw thread, cylindrical taper-4 keyway, hexagonal prism & triangular prism.

The first step in characterizing the welds was a visual inspection and qualitative analysis of the weld roots and crowns. Excessive lateral flash was observed in the welds, resulting from the outflow of the plasticized material from underneath of the shoulder (Figure-3). X-ray radiography of welded specimens were also carried out to check that no defects like root flaws or kissing bond were present in the welds. For most of the welds no flaw or defect was detected on the weld but in few joints some defects were revealed like insufficient fusion, lack of penetration & cavity. The visual observation of the weld is presented in Figure-4, it is clearly seen that a sound joint was obtained.

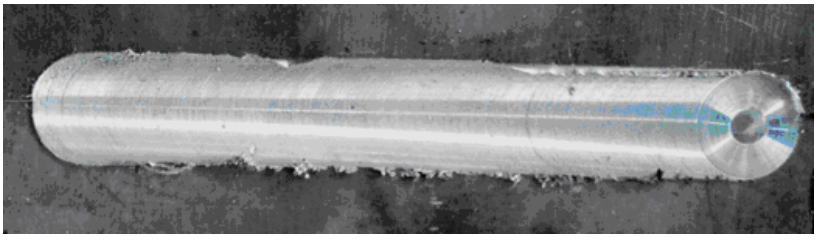

Figure-3 Lateral flash FSW in the joint.

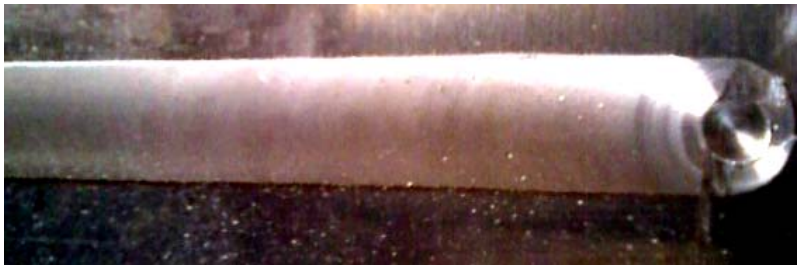

Figure-4 Visual inspection of FSW joints on top surfaces.

4.2 Mechanical Test Methodology: Mechanical properties of the test welds such as yield strength, tensile strength and percentage of elongation were assessed by means of static tensile test that evaluates. The welded joints are sliced using power hacksaw and then machined to the required dimensions to prepare tensile specimens as per ASTM guideline shown in Fig. 5.

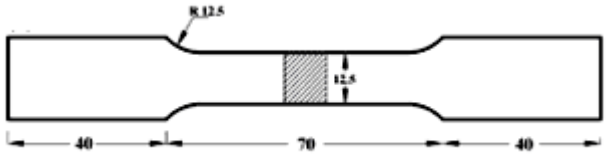

Figure-5 Tensile test specimen

4.3 Metallography Test: The micro-structural analysis of the friction stir processed samples was carried out by De-winter optical microscope. Cross-sectioning of the welds for metallographic analysis in planes perpendicular to the welding direction and parallel to the weld crown was also performed. The samples were prepared according to standard metallographic practice and etched with Keller's reagent (2ml HF (48%) + 3ml HCl + 5ml HNO_3 + 190ml H_2O) to reveal the grain boundaries.

4.4 Corrosion Behaviour : The corrosion resistance was carried out by using three electrode potentiodynamic method. The potentiodynamic scan was performed with a scan rate of 0.5mV/s by using potentiostat apparatus supported by corrosion measurement software. Friction stir zone as working electrode, graphite as auxiliary electrode and saturated calomel electrode as reference electrode were placed in a tank with 3.5% water solution NaCl. The samples were exposed (1 cm^2) such that only the friction stir zone is subjected to the corrosion tests and the rest of the areas were masked. The polarization was carried out at changes in the potential speed of 0.5 mV/sec in the range of -0.5V to 1V

5. Results and Discussions:

FSW has become a very effective tool in solving the joining problems of profiled sheets with material continuity, without using different joining methods, particularly in case of aerospace industry, where high ductility and tensile strength are required. In the present work, different FSW butt welds of AA6082 & AA6061 plates were successfully obtained by varying the processing parameters and the welded joints were mechanically and metallurgically characterized

The yield strength and ductility of the aluminium alloys play major role in deciding weld quality of FSW joints and hence the formation of friction stir processing region. The yield strength, tensile strength, percentage of elongation of FSW AA6082/AA6061 joints has been measured with respect to rotating speed & welding speed. At lower rotation speeds, tensile strength of FSW joints is lower and increases correspondingly with increase in the rotation speed up to a maximum value. After that tensile strength decreases with increase in rotation speed. It is true irrespective of tool pin profile. As rotational speed increases, heat input per unit length of the joint increases

resulting in increase in temperature which causes grain growth & gives inferior tensile properties. At low rotation speed there is considerable increase in turbulence which destroys the regular flow behaviour and gives low tensile strength. Moreover due to low rotation speed it takes more time to move the plasticize mass from advancing side to the retreading side resulting in porosity, sticking of the mass to the tool. So an optimum rotation speed should be maintained. The dissimilar joints displayed intermediate mechanical properties.

As the welding speed increases, tensile strength of the joint also increases up to certain critical value and after that tensile strength decreases because higher welding speeds results in short exposure time in weld area with insufficient heat input per unit length and poor plastic flow of metal.

Tool pin profile has a significant effect on the joint structure and the mechanical properties of similar metals. It has a negligible effect on the mechanical properties of the 6061 and 6082 Al alloys. It deals only with the proper flow of the material.

With the increase in downward pressure, the tensile strength increases due to the phenomenon of work hardening. However with excessive increase in pressure, tensile strength decreases due to dynamic recovery.

In few FSW sample corrosion rate is low, so grain boundaries are observed due to etching effect. As E_{corr} value decreases, the corrosion resistance of sample decreases. With the increase in E_{corr} value corrosion resistance increases. All sample show passivation after longer time of exposure to corrosion media. For the same welding speed the hexagonal pin profile shows good corrosion resistance than triangular pin profile.

6. Conclusions & Future Work:

6.1 Conclusions:

Friction stir welding technology has been a major boon to industry since its inception and has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. Significant progress has also been made in the fundamental understanding of both the welding process and the structure and properties of the welded joints. With better quantitative understanding of the underlying principles of heat transfer, material flow, tool-workpiece contact conditions and effects of various process parameters, efficient tools have been devised. At the current pace of development, FSW is likely to be more widely applied in the future. The objective of this research which is to characterize the mechanical properties and studying the microstructures of the friction stir welded alloys fabricated of similar and dissimilar alloys of Al was successfully achieved. The optimal conditions for obtaining a good welded joint is a rotational speed of 1600 rpm, feed rate of 68-74 mm/min and downward pressure of 11KN for AA6082T_6, rotational speed of 1600 rpm, feed rate of 50 mm/min and downward pressure of 12KN for AA6082T_6, rotational speed of 2000 rpm, feed rate of 70 mm/min and downward

pressure of 14KN for AA6082T_6, rotational speed of 1400 rpm, feed rate of 55 mm/min and downward pressure of 11KN for AA6061T_6, rotational speed of 1700 rpm, feed rate of 60 mm/min and downward pressure of 11KN for AA6061$T_{6,}$ rotational speed of 1600 rpm, feed rate of 50-70 mm/min and downward pressure of 14KN for AA6082T_6-AA6061$T_{6,}$ rotational speed of 1600 rpm, feed rate of 50 mm/min and downward pressure of 14KN for the joining of the dissimilar alloys of aluminum of AA6082T_6-AA6061T_6. Consequently, the obtained results explain the variation of stress as a function of strain and the effect of different welding speed and pin profiles on yield strength ultimate tensile strength and elongation.

6.2 Future Work:

The present research work has provided a fundamental understanding of FSW process & feasibility of incorporating this technology with existing resources to weld aluminium alloys in the abutting configuration and characterized mechanically & metallurgicaly, which covered tensile testing and microstructural development, as well as corrosion behavior in AA6xxx welds. Future work is still required to quantify the FSW process with variable weld process parameters that would concentrate on the following aspects:

- To study the effects of temperature distribution on the mechanical and metallurgical properties AA 6082T_6 / AA6061T_6 joints
- Other important developments that need attention will be to weld at higher feed-rates. This is important since it will drop the production cost and make FSW a more efficient process.
- To make the process to be operated at lower Z-Forces and without any backing plates it will make many other weld configurations possible.
- Improvement in tool design will always be an advantage since it plays an important role during weld quality. A new tool that can weld at lower forces, achieve better surface finishes and improve the tensile strength of the joint, are to be considered.

List of Research publications:

International Journal Papers:

1. H. S. Patil, , Dr. S. N. Soman, Effect of tool pin profile and friction stir welding speed on tensile properties of friction stir welded joints of AA6082 aluminum alloy. International Journal of Emerging Technologies and Application in Engineering, Technology and Sciences (ISSN: 0974-3588) Vol.3,No 1, Jan-June 2010, pp 203-206
2. H. S. Patil, S. N. Soman, Experimental study on the effect of welding speed and tool pin profiles on AA6082-O aluminium friction stir welded butt joints.

International Journal of Engineering, Science and Technology (ISSN 2141-2839, online journal) Vol. 2, No. 5, 2010, pp. 268-275.

3. H. S. Patil, S. N. Soman, Influence of process parameter on tensile properties of friction stir welded butt joints in 6082 aluminium alloy. International journal (ISSN 2229 -712X Elixir Online journal). Elixir Mech. Engg 30 (2011) 1823-1825
4. H. S. Patil, Dr. S. N. Soman, Structural Stress Analysis of Friction Stir Welding Tool Pin Profiles. International Journal of Mechanical Engineering and Materials Sciences (ISSN: 0974-584X) Vol.-4 No.1 Jan-June-2011.

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